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The development of an experimental technique for procuring shadowgraphs of the combustion process within a turbo-jet combustion chamber.

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THE DEVELOPMENT OF AN EXPERIMENTAL TECHNIQUE FOR PROCURING SHADOWGRAPHS OF THE COMBUSTION PROCESS WITHIN A TURBO-JET COMBUSTION CHAMBER

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

The need for a means of analyzing the combustion process within a turbo-jet engine to improve combustion efficiency has become of major importance in the jet engine field and ranks with the need for higher heat resistant alloys. One means by which it is possible to attain part of the information needed to analyze the combustion process is the attaining of schlieren photographs or shadowgraphs of the combustion process. This paper describes the problems involved in obtaining a shadowgraph of a turbo-jet combustion chamber as well as recommendations to overcome these problems. The problem of obtaining schlieren photographs would be of a similar nature.

The design of the test equipment needed for this work is presented as well as the technique for its use.

The two most serious problems encountered were those of attaining a properly designed two dimensional turbo-jet combustion chamber, and the over exposure of the film by the combustion flame. These two problems resulted in shadowgraphs only of the hot combustion gases after combustion and not of the combustion process itself.

The results obtained, although not final, form a basis for further development in this field.

INTRODUCTION

In the design of a turbo-jet combustion chamber, consideration must always be taken into account of the following requirements:

(a) Low plant weight

(b) Small frontal area

(c) Low pressure loss

(d) High combustion efficiency

(e) Uniform temperature distribution at outlet

(f) Stable operation

Of the six requirements listed, the latter four present a great problem to the designer. This is brought about by the complicated conditions that exist within the combustion chamber, where the large rates of heat release required by turbo-jet engines operating with high cycle temperatures and pressures introduce fundamental problems for the solution of which there exists no really adequate theoretical nor experimental background. As a result, the design procedure of the combustion chamber usually follows the pattern of initially incorporating proven concepts, whereafter endless time is spent in the experimental laboratory refining the combustion efficiency on practically a cut and try basis.

For example, it is known that the rate of diffusion of fuel droplets and fuel vapor in turbulent flow is many thousand times that in smooth or laminar flow. This fact is used to a great extent in the turbo-jet combustion chamber to provide a uniform air-fuel mixture for the efficient combustion in a small space. However, turbulent flow is created only at the expenditure of energy resulting in a static pressure drop along the combustion chamber. As is stated in Ref. 1, the problem of achieving the necessary turbulence for mixing with a minimum loss of pressure is a question that as far as is known remains an unknown to date. To find a method of analyzing the structure and the character of the turbulent motion in various geometrical arrangements of the combustion chamber would provide a very helpful step in obtaining this data.

Another helpful step in this field would be to find a visual means for determining the depth of secondary air flow penetration into the combustion gases to assist in ascertaining proper means for obtaining uniform temperature distribution at outlet, as well as an insight to stable operation.

With these considerations and problems in mind, it is the purpose of this paper to investigate the possibility of obtaining satisfactory shadowgraphs of the combustion process within a turbo-jet combustion chamber by attempting to develop a

technique for the experimental procedure in obtaining these photos. The obtaining of these pictures would lead to a simplification of the experimental procedure in combustion chamber design.

The principle of the shadowgraph, as its name implies, is simply to take a picture of the shadow of the density-change pattern within a medium. The degree of shadow or darkness at any point is dependent on the rate of change of density gradient with respect to a particular direction, i.e., $\partial \rho^2 / \partial x^2$.

The shadow is produced by the slight differences in index of refraction of the gaseous medium and results in dark areas for regions of increasing rate of change in density, light areas for regions of decreasing rate of change, and no change in the light intensity in regions of constant change. A changing density gradient may be caused by waves traveling through the medium, by air flow, or by temperature differences. The latter two are primarily responsible for any density gradients in turbo-jet combustion chambers.

The above synopsis of shadowgraphs reveals the fact that results are obtained only in the plane normal to the light path. Thus, in order to obtain a shadowgraph of the combustion process within a turbo-jet engine, it is first necessary to construct a

two dimensional chamber. As complete information was not readily available on any commercial combustion chamber, the basis used in designing a two dimensional version was in accordance with the method developed in the Master's Thesis, "The Analytical Design of a Turbo-Jet Combustion Chamber," by James B. Verdin (Ref. 2). The design procedure along with calculations for the chamber used in this work are given in Appendix A, and the chamber is shown unassembled in Figure 4.

The technique for procuring shadowgraphs in supersonic wind tunnels has been developed to a high degree, but so far as is known no development of this type has been made in the turbo-jet combustion field. The reasons for this lag in the turbo-jet combustion field are the necessity for a two dimensional chamber, which has not been developed, the high light intensity within the chamber, and the necessity for a means of viewing the inner part of the chamber where high gas pressures exist at temperatures approaching 3500° F. An attempt to overcome these difficulties is described in this thesis.

EQUIPMENT

Combustor

The combustor used in this development was designed and built specifically for this work. The design followed that developed by James B. Verdin in his Master's Thesis entitled, "The Analytical Design of a Turbo-Jet Combustion Chamber", (Ref. 2), the only exception being the two dimensional flow characteristics of this chamber. This two dimensional flow is in difference with the flow in the customary, circular, cross section combustion chamber. The analytical development of this combustion chamber is given in complete detail along with the calculations involved in Appendix A.

A photo of the chamber less fuel nozzle, glass ports, and one set of side plates, is shown in Figure 4. Figure 2 and Figure 4 show the locations of the primary and secondary air holes into the inner basket. The first three sets of circular holes are for the entrance of primary air, and the volume of the chamber from the after end of the primary holes to the forward end of the chamber is called the primary zone. It is in this zone that the majority of the fuel is vaporized, mixed with air, and burned. All the holes after the first three sets are the secondary holes, wherein air enters to mix with the hot, primary

gases flowing through in order to lower the temperature of the hot, combustion gases before they leave the tail section. In addition to that which enters through the three sets of circular primary holes, approximately one fourth of the primary air enters the chamber by means of the slits at each end of the semi-cylindrical forward section and through the holes behind the deflecting baffles on either side of the fuel nozzle. This air is for the purpose of cooling and for carbon prevention. The combustion chamber, with the exception of the side plates, was constructed entirely of 16 gauge stainless steel welded together to hold its shape and dimensions.

Each side of the chamber consisted of three sections of 1/8 inch thick mild carbon steel plate. The forward and aft sections of the side plates were held firmly against the main combustion chamber form by the tightening of several bolts which extended from one side plate to the other, thus sealing the chamber at these positions. The center section of the sides, however, was a sliding section. This was made moveable in order to attain easy access to the inside of the glass ports, which required frequent cleaning, and to allow the chamber to be started with the glass ports off to one side of the chamber. Thus a minimum of carbon was deposited on the glass before the spark photos were taken. The inner side of the sliding plate was held

flush against the main chamber section by a flange riveted along the forward and aft side plates. This formed a channel along which the center section would slide. A system of pulley and wires extending from the sliding plates out to the control station of the test cell provided a means of sliding the glass ports over the chamber proper when all was ready for taking a picture.

In order to keep the inside surface of the sliding plate flush, it was necessary to install the windows by beveling the glass and plate as shown in Figure 1.

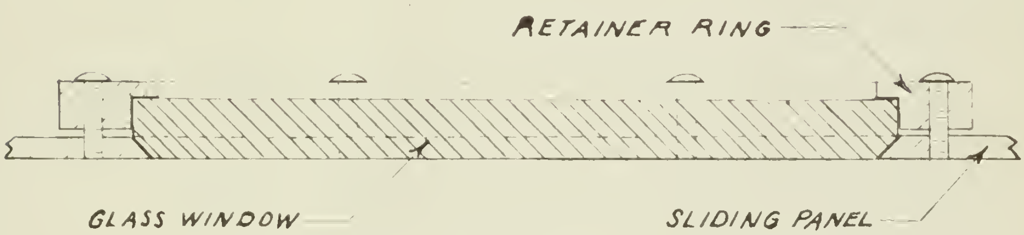


Figure 1. Cross section of glass port installation on sliding panel

The glass was then held flush against the sliding plate by means of a steel retainer ring fastened to the sliding panel by means of six small bolts.

The glass ports themselves were manufactured by Corning Glass Works. The glass was Vycor Brand 7900, which is 96% silica and capable of withstanding a temperature of 2000° F as well as extremely sudden temperature changes.

The ignitor plug may be seen mounted in Figure 5 just above the glass window. The fuel ignition system employed is that of a high intensity spark combined with an acetylene gas jet. The acetylene gas is fed into the cooling air space between the electrodes and the surrounding ceramic insulation. This insures a positive initial burning and eliminates explosive hot starts. The spark plug used was set outside of the fuel nozzle spray angle so as not to interfere with the two dimensional fuel spray characteristics.

The fuel injector system for the combustor consists of an electrically driven fuel pump, a rotameter, and one fuel nozzle. The fuel nozzle, manufactured by Spraying Systems Company, Chicago, Illinois, was unique in its two dimensional, 73°, fan type spray characteristics. Replaceable tips of varying orifice size were available to attain desired atomization at varying fuel flows.

An adapter of stainless steel was made for the forward and aft ends of the chamber so as to make connections with the

existing inlet and exhaust fittings of the test cell. The exhaust adapter was fitted with a total and static pressure tap as well as a thermocouple for obtaining chamber outlet conditions. Just ahead of the forward adapter similar fittings were installed to obtain inlet conditions.

Photographic Equipment

To prevent fogging of the negative by the combustion flame, a shutter was designed especially to cut down the time of exposure of the film to the flame within the combustion chamber. The shutter may be seen in the set-up photos, Figures 5 and 6. It consisted essentially of a 2.5 ft. by 1.5 ft., 3/4 inch thick plywood mount to which was attached a two ft. (diameter), aluminum disk and a set of springs for actuating the disk.

When stretched eleven inches each, the two springs produced a pull of sixty lbs. upon a seven inch pulley to which in turn the two ft., aluminum disk was attached. A 3/3 inch, steel pin, when placed through the pulley, disk, and plywood mount, held the shutter in a cocked position when under the spring tension. Upon removal of this pin, the disk was accelerated to a speed of approximately fifty radians per second, at which point a four inch hole in the disk with center eight inches out

from the center of the disk reached a velocity of approximately 400 inch per second. When this hold was directly behind the glass ports in the combustion chamber and at the same time uncovered a four inch hole in the plywood mount, the spark was initiated by means of a lip on the circumference of the disk. The spark circuit was originally closed by placing a piece of aluminum foil between the leads to the actuating switch, thus making a contact which was easily and positively broken when cut by the disk. It was possible to make slight adjustments in timing by moving the aluminum foil forward of a dead center position which was marked on the plywood mount.

In order to prevent double exposure of the film to the flame, the disk was braked by a foam rubber pad which was also actuated by the lip on the circumference of the disk. A stretched spring working on a lever arm to which the rubber pad was attached furnished the braking force. When the brake was cocked, a pin between the lever arm and the shutter mount held the rubber pad off the disk. This pin was carried away when contacted by the lip on the disk.

A 4 by 5 Graphflex film holder was attached to the back of the plywood mount by means of a tenon built on the mount to fit the mortise of the film holder. This produced a tight fit that eliminated any light leaks from an external source. Only

when the four inch hole in the disk was over the four inch hole in the plywood mount could the film be exposed. The back of the aluminum disk, the front of the shutter mount, and the 3/4 inch hole in the mount were painted a dull black to eliminate any light from reaching the film if such should enter through the very small space between the disk and the mount. The calculations for determining the approximate speed of the shutter are presented under "Calculations."

The light source for the shadowgraphs was obtained from a 7000 volt discharge across a pair of electrodes. The enclosure for the electrodes contained a small hole in a black rubber diaphram to emit what is equivalent to a point source of light. The duration of the spark was approximately two microseconds and the delay between the breaking of the circuit in the spark actuator and the discharge of the spark was approximately two to three microseconds.

Test Setup

The arrangement of the test setup is shown in Figures 6 and 7. Air for the combustion chamber was supplied by the auxiliary compressor section of a 1710 Allison Vee 12 engine and is

seen in Figures 6 and 7 as coming down from the top of the photo in a six inch duct. Desired air flow through the compressor was obtained by regulation of the Allison engine speed. The air mass flow was measured by a thin plate orifice located upstream of the compressor.

All pressure and temperature pickups were lead out of the test cell to the control panel where complete control of the entire test setup was maintained during firing runs.

PROCEDURE

A check on the coordination of the spark and shutter was first made with the combustion chamber inoperative. This was accomplished by cocking the shutter and inserting the aluminum foil at positions varying from dead center (at which position the trigger lip cut the aluminum foil at the instant the glass ports were in line with the hole in the disk and the hole in the plywood board) to $\frac{1}{2}$ inch before dead center. This variation of $\frac{1}{2}$ inch was equivalent to approximately one thousandth of one second variation in triggering time. Figure 8 was obtained with the aluminum foil ahead of dead center by approximately 1/16 inch. This position was the best centered of the four runs made; therefore it was sought to be duplicated in all ensuing runs.

These initial runs also served the purpose of obtaining the pattern of striations within the glass. This procedure must be repeated whenever the glass is removed or replaced.

Various rates of air flow were then controlled through the combustion chamber without firing or injecting fuel into the chamber. For each run the static and total pressures as well as the temperatures were recorded for both the inlet and the outlet stations of the combustion chamber. These runs at varying air flows were made only to obtain an idea of the friction pressure

drop through the combustion chamber. At the design air flow of one pound per second a shadowgraph was taken to obtain the air flow pattern in the primary zone.

A duplication of the above runs was attempted with the combustion chamber burning. However, this was soon terminated when after a run of approximately one minute's duration at 1500° F outlet temperature and while adjustments were still being made to fuel flow and air flow, the sliding center sections of the combustor sides began to warp, emitting flame into the test cell.

After repairing the sliding panels, the equipment was used only for developing a technique in procuring shadowgraphs of the combustion within the chamber.

The two procedures used for taking the shadowgraphs are outlined below. The first procedure was used when the glass was positioned over the combustion chamber from the start of the operations, and the second procedure was used when the glass was off to one side of the chamber at the start.

First Procedure (Glass in position over combustion chamber)

(a) Cock the shutter and put a slight tension on the trigger cable which extends out to the control panel.

(b) Start the Allison engine and attain the desired

air flow through the combustor (1 lb/sec).

(c) Energize the photo spark system and place loaded film holder in position on plywood mount.

(d) Actuate ignitor button to start the acetylene ignitor flame and hold until fuel oil in combustor ignites.

(e) Start fuel oil pump and open fuel oil flow valve until desired exhaust temperature is reached.

(f) Pull cable to trigger shutter.

(g) Shut off fuel oil, Allison engine, and remove film holder.

Second Procedure (Glass off to one side of combustion chamber)

The procedure is identical with the first procedure through step (e), after which it is necessary to pull into position the glass ports by means of the cable pulley system extending from the sliding panels of the combustor to the control panel. Steps (f) and (g) then follow in order.

Photos were taken for each of the three configurations of the combustion chamber test. The three configurations were:

1. No 1 fuel oil burned in the chamber, using a fan spray nozzle with a flow rating of .074 gallons of water per minute at 40 psig.

2. Acetylene burned in the chamber, using the same fuel nozzle as in configuration 1.
3. No 1 fuel oil burned in the chamber, using a fan spray nozzle with a flow rating of .039 gallons of water per minute at 40 psig.

RESULTS AND DISCUSSION OF TECHNIQUE

Figure 8 is a shadowgraph showing the basic pattern of the glass striations and the proper triggering time of 1/16 inch before dead center position. This picture was taken with no fuel or air flow through the chamber and therefore represents only the effect of the glass. The striations within the Corning Glass Works Vycor 7900 glass, although reported by the manufacturer to be only slight, actually are near the point of being excessive for shadowgraph work. It should be noted, however, that in the shadowgraph of Figure 12 these striations are barely discernible among the turbulent flow pattern of the chamber. In the case where small density gradient changes are involved, as when taking a shadowgraph of the turbulence within the chamber with air flow only passing through the chamber, as in Figure 9, the striations may readily obscure any pattern present.

Table II presents the data taken for the cold runs of air flow passing through the chamber without fuel flow. These runs were taken for the purpose of obtaining the friction pressure loss through the chamber. Figure 3 shows a plot of the ratio of friction pressure loss to entrance pressure versus air flow. The friction pressure loss ratio at an air flow of 1.0 lbs/sec was 12½%, which is three times the value used in the combustion

chamber calculations. A large part of the difference may be accounted for by the fact that the pressure drop in the inlet air adapter was included in the test runs, whereas this was not accounted for in the analytical design and rightfully should not be included as part of the combustion chamber pressure loss. An uneven edge at the junction of the adapter and the chamber was present in the actual unit and could cause a considerable pressure drop. Two other factors which would cause this greater pressure drop are the air leaks about the sliding center section and the fuel tubing at the intake which is at right angles to the air flow direction.

During these cold runs with no fuel flow, the shadowgraph Figure 9 was taken at an air flow of .95 lb/sec. No pattern of the incoming air flow is perceptible in this photo. In other words, the change in density pressure gradient is not sufficient at an inlet pressure of 1.2 atmospheres (as was the case in this run) to produce a shadowgraph in the primary zone.

At this point it may be well to discuss the actual operation of the two dimensional chamber with the analytical design, as the difference between the two resulted in the inability to obtain a satisfactory fuel air ratio in the primary zone. The chamber was designed for a one lb/sec air flow at an inlet pressure of 1.6 atmospheres. In the actual chamber this air flow

was obtained at an inlet pressure of approximately 1.2 atmospheres. The pressure drop equation used in computing the flow through the orifices of the combustion basket has been verified in Ref. 3 as giving results in close agreement with actual conditions. This leads to the conclusion that the effectiveness coefficient, C_e, used in computing the flow through the secondary holes, is much too low. This coefficient was used to make a correction to the weight flow through an orifice when the flow precedes through the orifice at an angle other than normal to the orifice. Further investigation of this coefficient is necessary to adequately justify its use. The use of this coefficient increased the total orifice area of the secondary zone by approximately forty per cent, and it resulted in excess air flow through the secondary holes in the burner basket, leaving insufficient air flow through the primary holes. This lead to a very dense orange-yellow flame in the primary zone, due to the excess fuel present.

In the attempts to take shadowgraphs under this flame condition, no success was obtained with the apparatus used. All negatives were completely exposed by the flame itself, with the result that if any shadowgraph of the flame pattern were obtained it was blanked out by the exposure of the film to the flame.

It was here realized that a major modification to the

film exposure technique was necessary to obtain a shadowgraph of the combustion process with a yellow flame present. The 1/100 second exposure produced by the shutter was too lengthy for the direct method of film exposure used. It is concluded that in order to obtain shadowgraphs of the combustion process within a turbo-jet combustion chamber it is necessary to displace the shutter and film from the combustion chamber by means of an optical train. By use of lenses, and possibly of mirrors to adjust to space limitations, most of the light from the combustor flame may be eliminated and not registered on the film.

As time and equipment were not available to make this modification in photographic technique, the combustion process itself was modified in an attempt to produce a blue flame, and the spark intensity was increased. A blue flame would allow greater penetration of the spark light with the absence of carbon and fuel particles and would also decrease the effect of combustion flame exposure on the film by decreasing the intensity of the flame light. To further increase the effect of the spark light, thereby overshadowing the effect of the flame light, the spark intensity was doubled by decreasing the distance from spark to combustion chamber from 8.4 feet to six feet. At six feet the light rays from the spark are only 1.5 degrees from a direction normal to the chamber's glass windows, which is still

within the satisfactory limits for shadowgraph work. More than a two degree divergence of the light source in shadowgraphs results in a loss of photo sharpness.

The first method tried for attaining a blue flame within the chamber was that of injecting acetylene in the chamber instead of fuel oil. Figure 10 is a shadowgraph of the chamber operating with acetylene. Sufficient acetylene was unavailable from its source to produce a flame in the chamber that extended beyond the glass windows. A flame of only approximately two to three inches in length could be attained. Thus Figure 10 shows only the heated gases in the forward half of the picture, whereafter the additional influx of air through the primary holes has chilled the gases sufficiently to obliviate any further visible shadow effect. The disconcerting effect of the glass striations is prominent in this shadowgraph. Were it not for the interference effect of the striations, the pattern of the incoming primary air might be well defined.

With insufficient acetylene flow available, a second means for obtaining a blue flame was developed by installing an undersize fuel nozzle in the chamber. The effect of this nozzle was to obtain better atomization of the fuel at low fuel flow rates. The low rate of flow was necessary to overcome the insufficient supply of primary air for reasons stated earlier.

With this lower fuel flow, a blue to light yellow flame was obtained which extended approximately half way across the glass window. It produced an exhaust temperature of 300° F at one lb/sec air flow and approximately 22 lb/hr. fuel flow. The latter was estimated at the low end of the fuel rotameter.

Figures 11 and 12 were taken under the above conditions. The fogging of Figure 11 and the lack of fogging of Figure 12 are enigmatic, as in both pictures the flame appeared approximately half way across the glass windows when viewed at time of exposure. Figure 11 did appear to have a slightly more yellow light in the flame than was the case in Figure 12. The only other difference in the exposure of the two was that Figure 11 was exposed by means of Procedure I, wherein the glass was in place over the combustion chamber during ignition of the fuel and while making adjustments to fuel flow. Under this procedure a slight brown tint appears over the inner surface of the glass. This tint accumulates mainly during the period of ignition when the acetylene is flowing from the spark ignitor.

Figure 12 was obtained under Procedure II, wherein the glass windows were off to the side of the chamber during ignition and fuel adjustment and were pulled into place just prior to triggering the shutter. In the upper left hand section of this shadowgraph the formation of the pattern is considered to

be that of a pinnacle of flame. When viewed through the window at time of exposure, the flame consisted of three or four pinnacles centered within the two inch wide chamber. The flame did not extend across the chamber from side to side. The absence of the pattern of primary air flow into the chamber is again considered due to the low rate of air flow into this zone through the three sets of primary holes.

It was necessary to discontinue the procedure at this point, due to the fact that a break down occurred in the fuel manifolding within the chamber inlet area. The breakdown was caused by a fuel pressure of 120 lb/sq. in. which resulted when the attempt was made to increase the length of the flame.

In the interest of anyone pursuing this work of shadowgraph photography of a turbo-jet combustion flame, the following suggestions merit consideration:

(1) If the design procedure for a two dimensional combustion chamber as outlined in Appendix A is used, the effectiveness coefficient, C_e, as used for purposes of obtaining the air flow through the secondary holes should be omitted entirely or else a further study should be made in this field to determine a proper coefficient. The chamber used in this work may be readily modified by blocking up that portion of the

secondary holes which is equivalent to the area added by the use of C_e. This would bring the chamber up to its design inlet conditions for the 1 lb/sec air flow.

(2) A sliding section to contain the glass window is a very desirable feature in this work. Once the chamber is operating with a blue flame, carbon deposit on the glass is negligible. However, when the glass is part of the chamber side during the initial starting, it becomes cloudy from the acetylene flame and from fuel oil deposits on the glass in a liquid form. The fuel particles left a dark brown deposit when eventually burned. The sliding feature also greatly facilitates cleaning of the windows. The sliding panel should be made of at least $\frac{1}{4}$ inch steel plate in order to reduce warping to a minimum and thus allow ease of sliding when the chamber is burning.

(3) It is desirable to have the window rectangular in shape rather than circular and to be of sufficient length to extend from one side of the chamber inner basket to the other. This would allow full observation of the air flow through the primary holes and ease the fabrication problem of attaching the windows to the sliding panel.

(4) An optical train of lenses is considered a necessity to reduce the effect of the flame light on the film. To manufacture a shutter that would give an exposure of 1/2000 second with a four to five inch diameter hole appears impractical, and this is considered to be a maxium exposure time allowable to adequately reduce the flame effect. The displacement of the film from the combustion chamber is also a desirable condition; for, when the film is close to the combustion chamber (as was the case in this work), the sensitivity of the film is greatly increased by the heat.

(5) The Vycor 7900 glass, 96% silica, used in this work withstood the high temperature and rapid temperature changes of the combustion chamber very well. On the other hand, the poor optical quality of this glass obliviates much of the shadowgraph when small changes in density gradient are to be observed. Additional expenditure for a good quality quartz windows would be worthwhile.

CONCLUSIONS

As a result of this work in the development of a technique for the procuring of shadowgraphs within a turbo-jet combustion chamber, the following conclusions may be made:

(1) Considerable work is necessary to first design and construct a two dimensional combustion chamber. The design procedure outlined in this report must be modified to obtain a satisfactory proportion of primary and secondary air flow.

(2) The sole use of a mechanical shutter is an impractical means to reduce the effect of flame light on the photographic film. An optical train of lenses combined with a shutter is necessary to reduce the effect of this light.

(3) A means for having the viewing section out of the chamber proper during ignition and adjustments of the combustion flame and then moved to the location where the shadowgraph is to be taken just prior to triggering the spark is a desirable feature. A channeled sliding section worked adequately in this development with the exception that, under design operating conditions of

1500° F exhaust temperature, excessive warping of the section was encountered.

(4) Vycor 7900 glass has an excessive amount of striations in it which interfere with satisfactory interpretation of the shadowgraphs. The additional expense of acquiring quartz windows is deemed advisable and also the obtaining of rectangular windows in lieu of circular windows.

Shadowgraphs only of the hot combustion gases after the combustion and not of the combustion process itself were obtained in this work. However the results, although not final, form a basis for further development in this field.

TABLE I

Summary of Combustion Chamber Air Inlet Areas

	Hole Diameter In.	Area Sq. In.	Accumulated Area Sq. In.	Distance from Nozzle (In.)
Dome Holes	5/16	.307	.307	0
Slit Between Dome and Inner Liner		.352	.659	1.65
Primary Holes				
1st set	13/32	.518	1.177	4.7
2nd set	13/32	.518	1.695	6.0
3rd set	13/32	.519	2.214	7.0
Secondary Holes				
1st set	1/2	.785	2.999	8.20
2nd set	5/8	1.227	4.226	9.6
3rd set	7/16	.301	4.527	10.1
4th set	5/8	1.227	5.754	10.6
5th set	7/16	.301	6.055	11.05
6th set	5/8	1.227	7.282	11.5
7th set	7/16	.301	7.583	11.95
8th set	5/8	1.228	8.811	12.4
9th set	7/16	.301	9.112	12.85
10th set	5/8	1.227	10.339	13.3

TABLE II

Recorded Air Flow Data Through Combustion Chamber

With Resulting Air Flow and Pressure Drop

ΔP	P_{4s}	P_{5s}	P_{4T}	P_{5T}	T_1	ΔP_f	$\Delta P_f/P_{T4}$	w_a
0.2	31.0	28.7	31.1	29.25	80	1.85	.060	.575
0.4	33.2	28.4	33.3	30.3	80	3.0	.090	.813
0.6	35.0	28.0	35.3	30.9	80	4.4	.125	.994
0.8	37.5	27.7	37.7	31.7	80	6.0	.159	1.147
1.0	39.5	27.4	39.9	32.5	80	7.4	.185	1.280
1.2	41.9	27.1	42.0	33.6	80	8.4	.200	1.400

Bar = 29.18 in Hg

where ΔP = nozzle velocity head

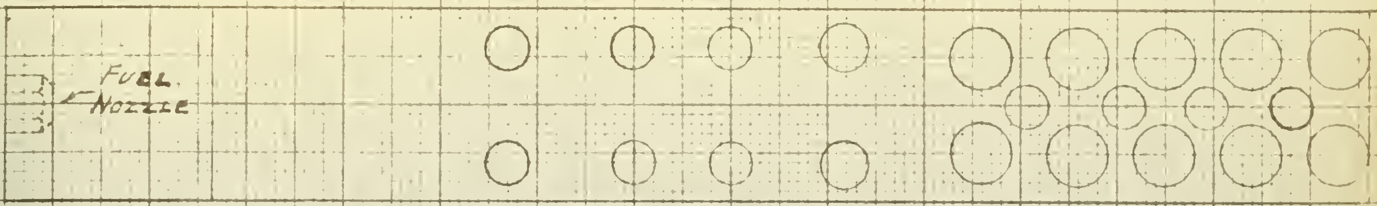
P_4 = inlet pressure, in. Hg

P_5 = exit pressure, in. Hg

T_1 = temperature of air through nozzle, $^{\circ}F$

ΔP_f = friction pressure drop

w_a = air flow lb/sec



LOCATION OF PRIMARY AND SECONDARY HOLES IN TOP OF INNER BURNER BASKET

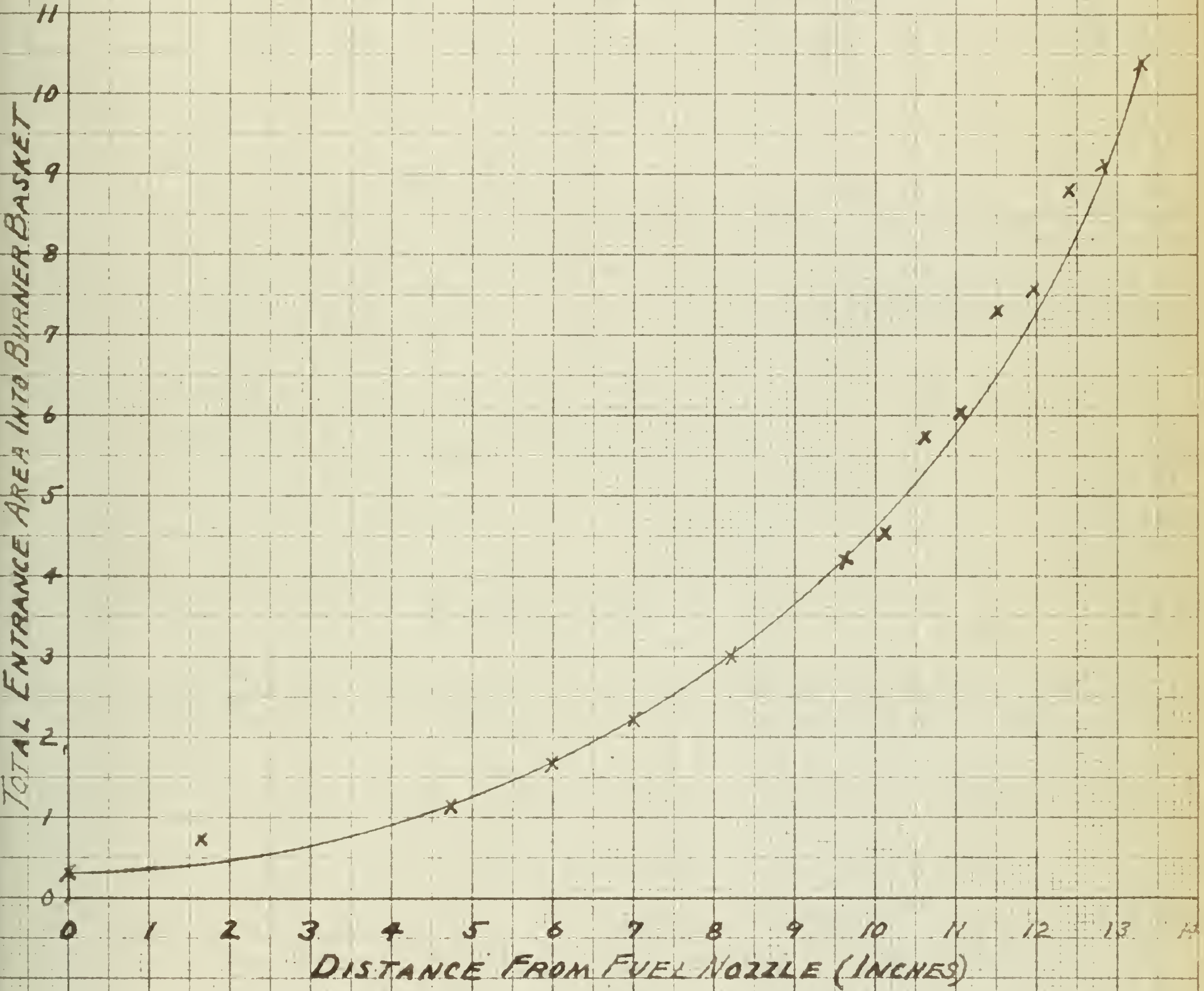
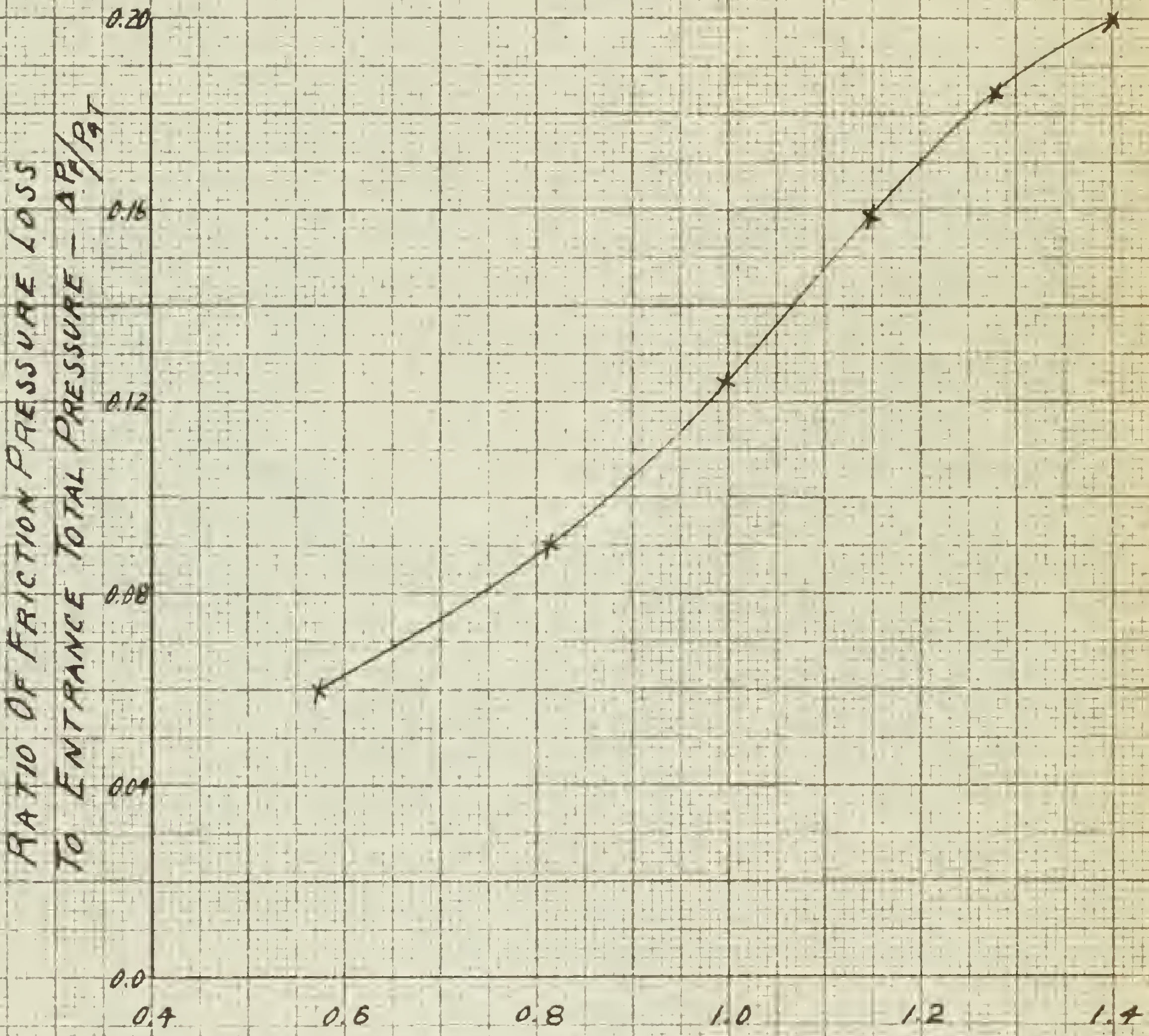


Fig. 2

CURVE USED IN LOCATING PRIMARY AND SECONDARY HOLES

Fig. 3

FRICTION PRESSURE LOSS THROUGH COMBUSTION CHAMBER VS AIR FLOW



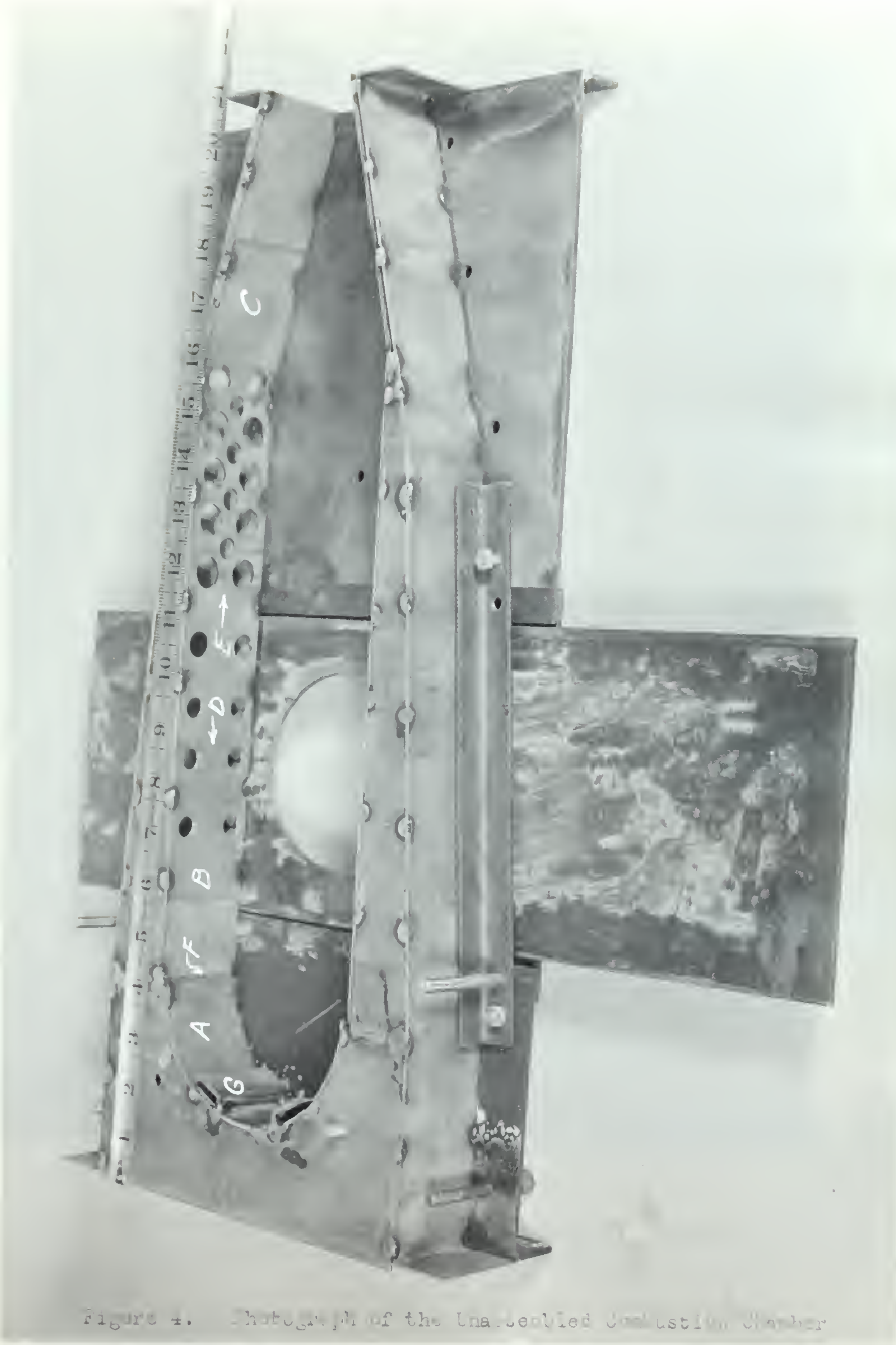


Figure 4. Photograph of the Unassembled Combustion Chamber

A. Dome or forward section
B. Rectangular or center section
C. Frustrum of Pyramid or tail section
D. Primary holes
E. Secondary holes
F. Cooling slit
G. Cooling holes behind baffle

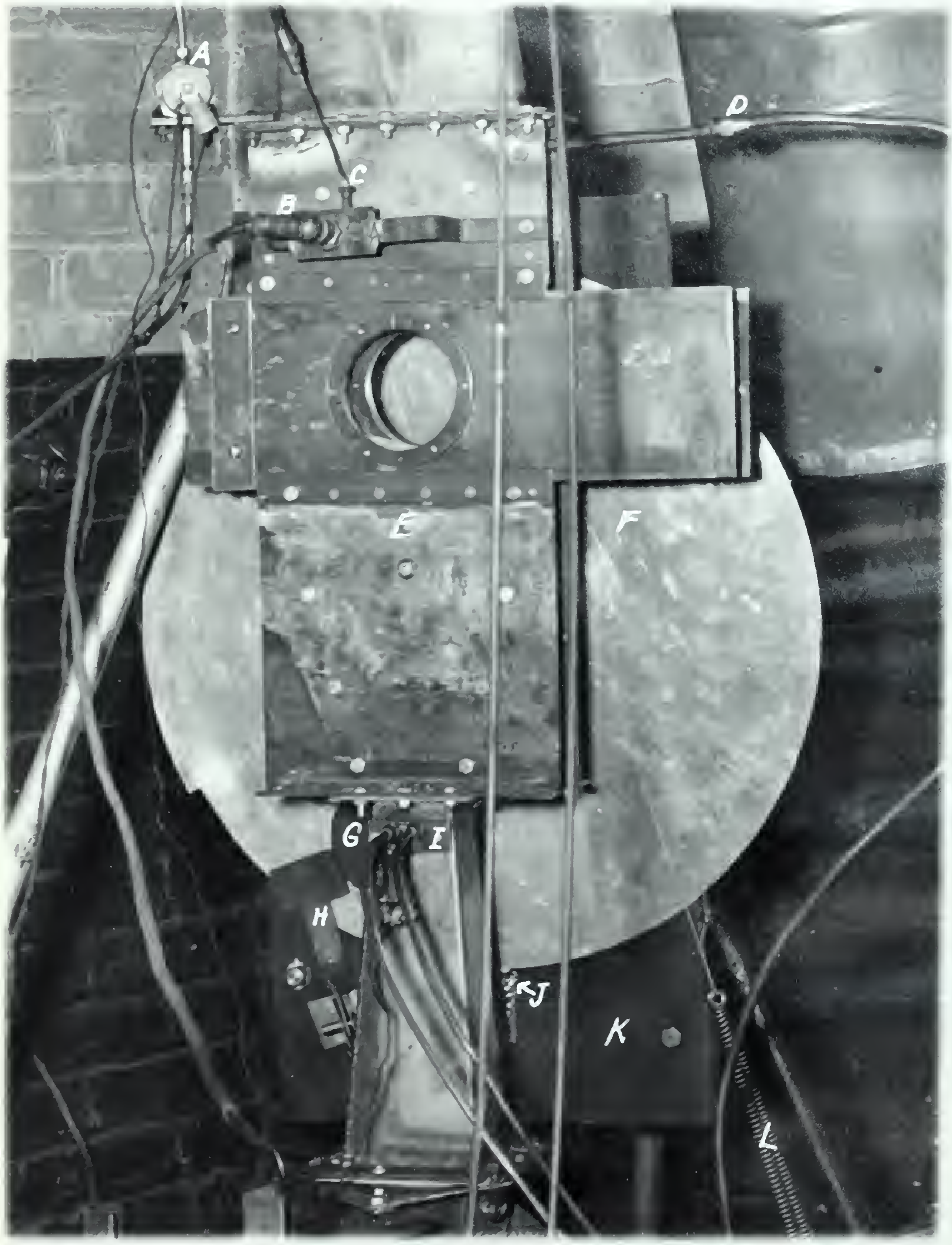


Figure 5. Closeup View of Installed Chamber and Shutter

A. On-off solenoid for acetylene
B. Ignitor plug
C. Acetylene line
D. Fuel line
E. Combustion chamber
F. Aluminum shutter disk, cocked position
G. Portion of shutter opening
H. Shutter brake
I. Adapter for exhaust temperature and pressure leads
J. [illegible] foil spark trigger
K. Plywood mounting board
L. Shutter actuating spring

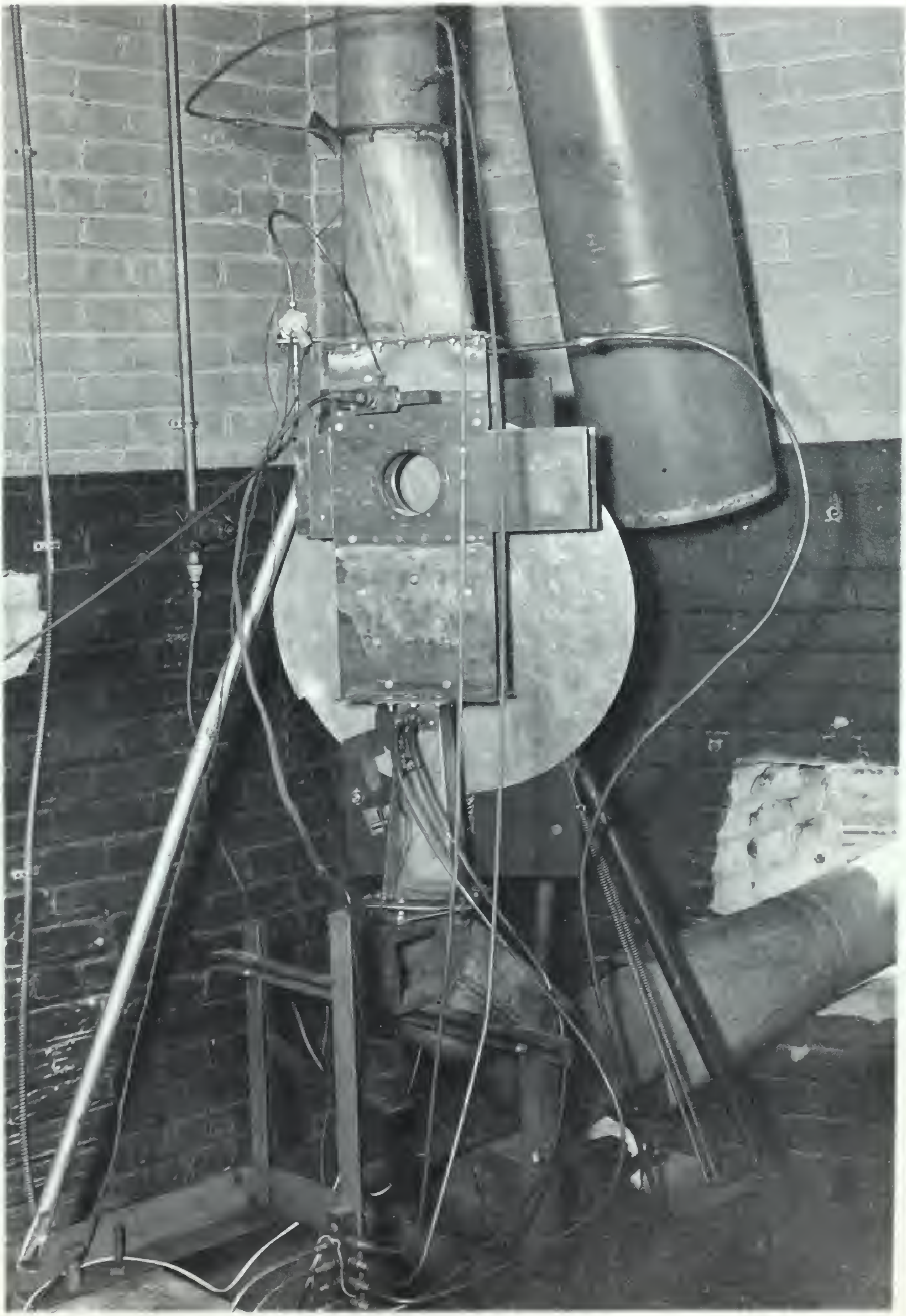


Figure 7. Front View of Test Rig

Figure 8. Shadowgraph of Glass Striations

(Top of shadowgraph is toward forward end of combustion chamber, bottom is toward after end of combustion chamber)

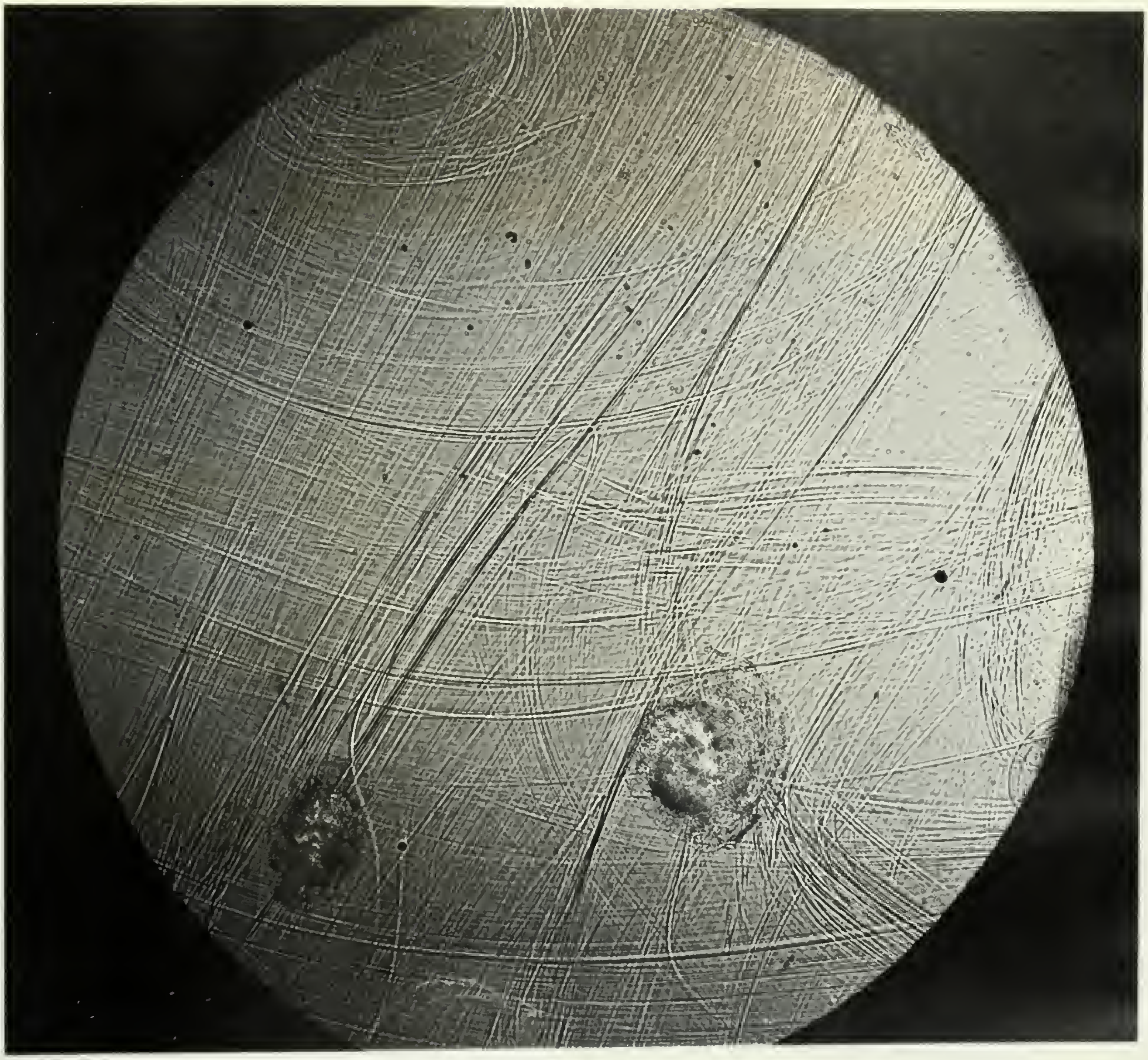


Figure 8. Shadowgraph of Air Flow Only Through Combustion Chamber

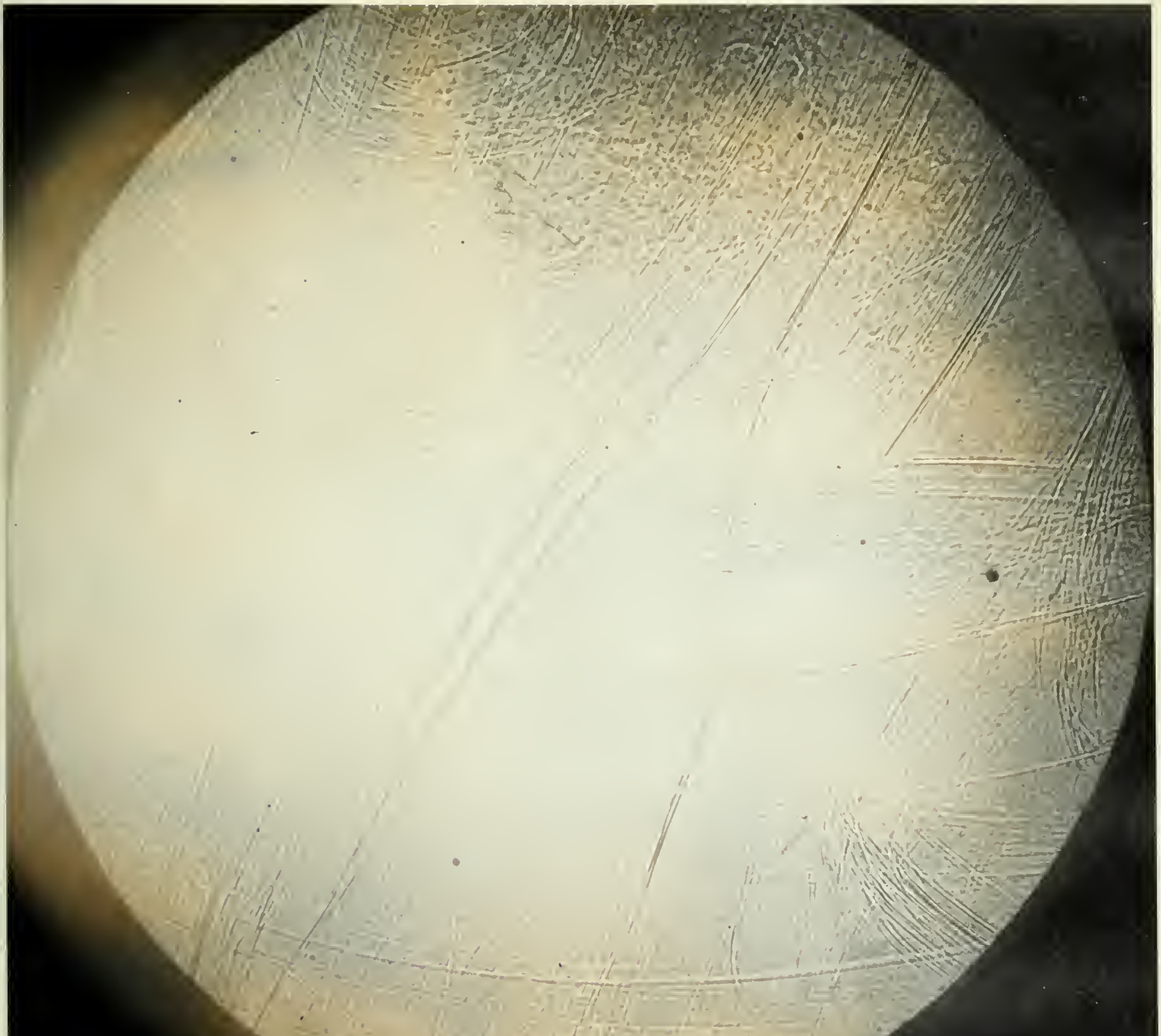


Figure 10. Shadowgraph of Combustion Gases of Acetylene Flame

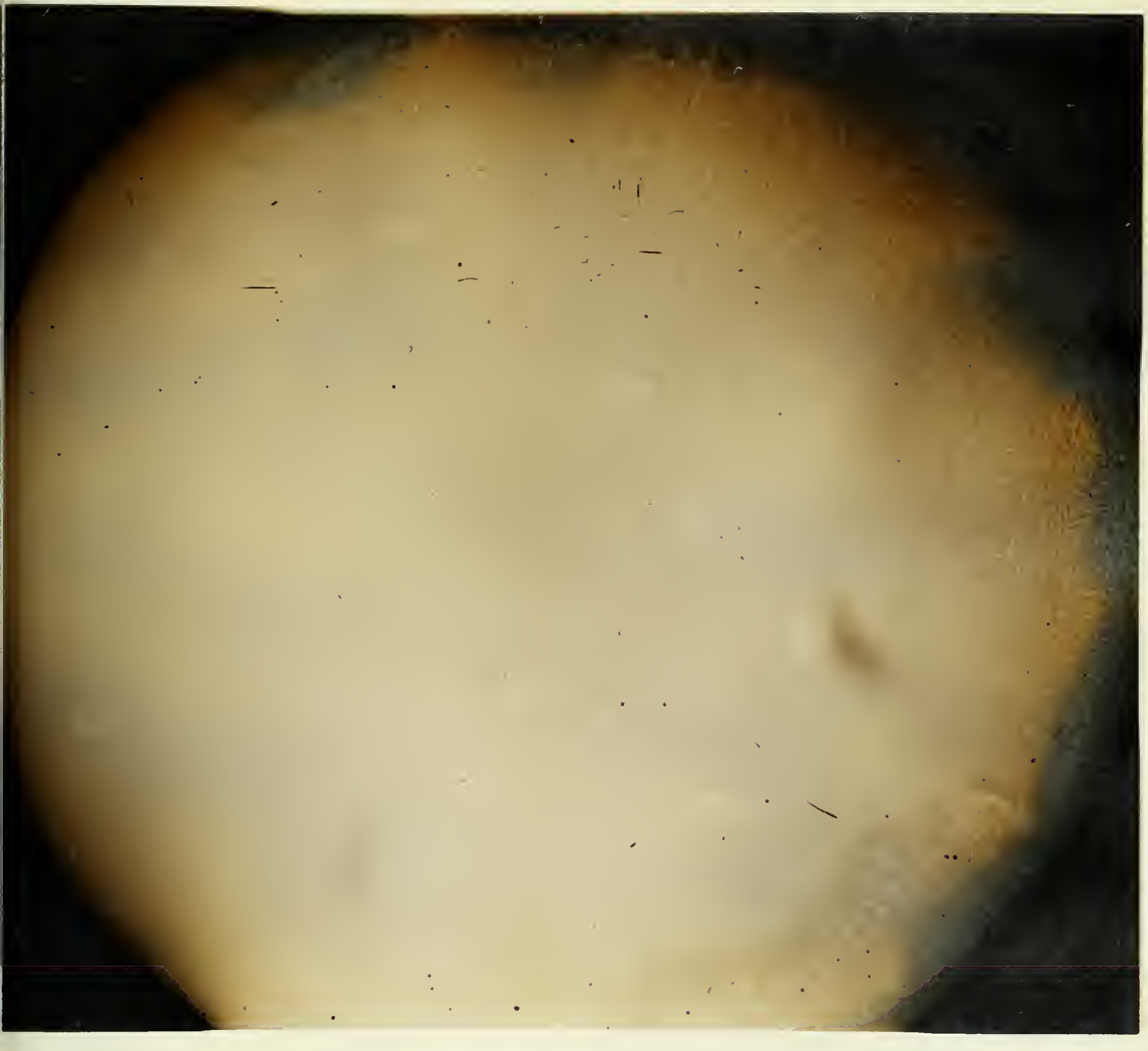


Figure 11. Shadowgraph of Combustion Flame

(Black lines and dots are markings on negative)

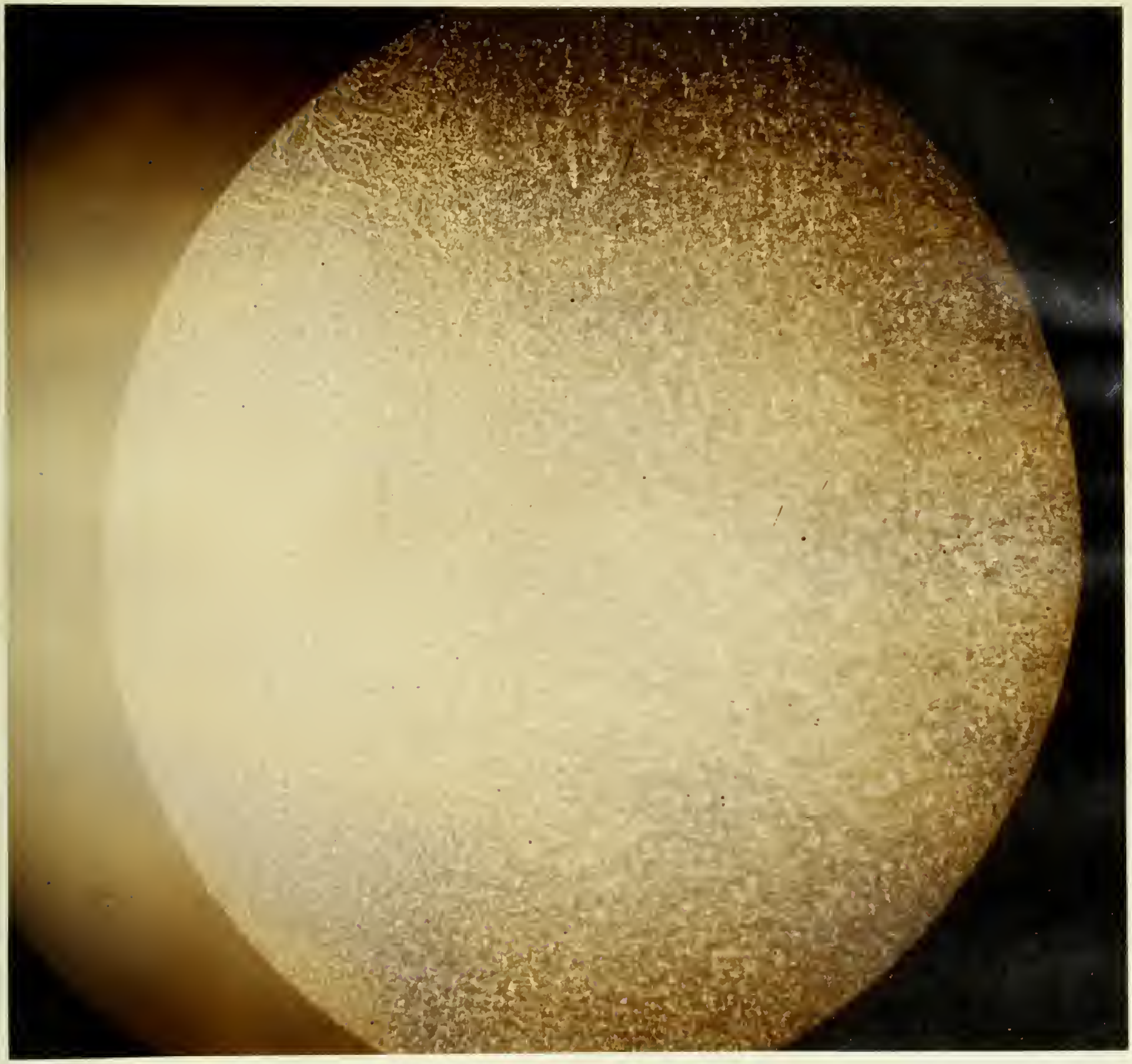


Figure 12. Shadowgraph of Combustion Flame

Appendix A

COMBUSTION CHAMBER DESIGN

Design Point

The design point was selected in general to conform with the design factors as used in current turbo-jet engines. However, they could not be followed strictly due to the limitation of the material and equipment available for constructing and operating the combustion chamber. This resulted in sea level conditions and a low inlet pressure of 1.6 atmosphere.

The design point selected is:

Altitude = sea level

w = 1 lb./sec., airflow

P_{4T} = 1.6 atmosphere, total inlet pressure

T_{4T} = 200° F or 660° R, total inlet temperature

T_{5T} = 1500° F or 1960° R, total outlet temperature

V_r = 100 ft./sec., reference velocity

M_r = .08, reference Mach number

$I = 8 \times 10^6$, combustion intensity

b = 2 in., width of two dimensional flow

L/H = between 3 and 4

l/H = between 2 and 3

where l = length in inches from fuel nozzle to end of basket

L = Length in inches from fuel nozzle to turbine entrance

H = Height of basket in inches

Maximum Height of Combustion Chamber

$$V_r = M_r(a)$$

where V_r = reference velocity in ft./sec.

M_r = reference Mach number

a = speed of sound in ft./sec. = $49\sqrt{T_{4T}}$

$V_r = .08 \times 49\sqrt{T_{4T}}$

$= 100$ ft./sec.

$$\rho = \rho_{sc} \times \frac{P_{4T}\, T_{sc}}{P_{sc}\, T_{4T}}$$

where ρ = density of air in lb./ft.^{3}

ρ_{sc} = density of air in lb./ft.^{3} at standard conditions

P_{4T} = total pressure in lb./ft.^{2} at entrance

P_{sc} = atmospheric pressure in lb./ft.^{2} at standard conditions

T_{sc} = temperature in $^\circ$R at standard conditions

$\rho = .07651 \times \frac{3380}{2116} \times \frac{520}{660}$

$= .0963$ lb./ft.^{3}

$$A = \frac{w}{\rho v_r}$$

where A = area of combustion chamber in ft.^{2}

w = airflow in lb./sec.

$$A = \frac{1}{.0963 \times 100}$$

$$= .1037 \text{ ft.}^2$$

$$h = \frac{A}{b}$$

where h = maximum height of combustion chamber in ft.

b = width of combustion chamber in ft. = $\frac{2}{12}$ ft.

$$h = \frac{.1037}{2/12} = .1222 \text{ ft.} = 7.47 \text{ in.}$$

Fuel Required

$$c_{pave} = \frac{c_{p4}+c_{p5}}{2}$$

where c_{pave} = average specific heat at constant pressure in Btu/lb. air °R

c_{p4} = specific heat at entrance to combustion chamber

c_{p5} = specific heat at exit from combustion chamber

$$c_{pave} = \frac{.240 + .277}{2}$$

$$= .259 \text{ BTu/lb. air } ^{\circ}\text{R}$$

$$q = c_{pave} (T_{5T} - T_{4T})$$

where q = heat required in Btu/lb. air

T_{5T} = total temperature at combustion exit in ^{o}R

$q = .259(1960 - 660)$

$= 337$ Btu/lb. air

$$w_f = \frac{qw}{LHV}$$

where w_f = fuel required in lbs./sec.

LHV = lower heating value of fuel in Btu/lb.

$$w_f = \frac{337 \times 1}{18500}$$

$= .0182$ lb. fuel/sec. $= 65.5$ lb. fuel/hr.

Primary Air Required

A stoichiometric mixture of fuel and air should exist in the primary zone for satisfactory combustion. Thus, the fuel air ratio must be .067.

$$w = \frac{w_f}{.067}$$

where w = weight of primary air required in lb./sec.

$$w = \frac{.0182}{.067} = .272 \text{ lb./sec.}$$

Volume Available for Combustion

$$V = \frac{q}{PI}$$

where V = volume available for combustion in $ft.^3$

q = heat input in Btu/hr.

P = pressure inside chamber in atmospheres

I = combustion intensity factor in Btu/hr.-ft.^{3}-atm

$$V = \frac{.0182 \times 3600 \times 18500}{1.6 \times 8 \times 10^6}$$

$$= .0948 \text{ ft.}^3$$

Configuration of Burner Basket

As shown in Figure 4, the burner is made up of three sections, semi-cylindrical segment, rectangular center section, and frustum of right regular pyramid tail section.

Giving:

$$V_T = V_C + V_S + V_{TC}$$

where V_T = total volume in ft.^{3} = .0944 ft.^{3}

V_C = volume of center section

V_S = volume of semi-cylindrical segment

V_{TC} = volume of tail section

Then,

$$V_T = \frac{b\pi D^2}{2 \times 4} + bHl_c + \frac{1}{2} \quad b(H + d)h$$

where D = inner diameter of semi-cylindrical segment

H = height of center section in ft.

b = width of combustion chamber = 2 in. = .167 ft.

l_C = length of center section

d = smaller height of tail section in ft.

h = length of tail section in ft.

Assuming $D = 4.5$ in. $= .375$ ft.

$H = 4.8$ in. $= .4$ ft.

$d = 2.1$ in. $= .175$ ft.

$h = 5$ in. $= 5/12$ ft.

$$.0948 = .00919 + .06671_C + .0200$$

Solving for l_C,

$l_C = .990$ ft. $= 11.9$ in.

Then $l = l_C + 2.25$

Where l = total length of inner burner from fuel nozzle to tail cone in inches

2.25 = radius of semi-cylinder at upstream end of basket in inches

$l = 11.9 + 2.25 = 14.15$ in.

Also,

$L = l + h$

Where L = length from fuel nozzle to end of tail cone in inches

$L = 14.15 + 5 = 19.15$ in.

Then

$$\frac{l}{H} = \frac{14.15}{4.8} = 2.95$$

And

$$\frac{L}{H} = \frac{19.15}{4.8} = 3.99$$

Since the values of l/H and L/H are between the desired values of 2 and 3 and 2 and 4 respectively, the dimensions of

the burner basket were selected as assumed and calculated in the foregoing procedure and may be summarized as follows:

$H = 4.8$ in.	$l_C = 11.9$ in.
$d = 2.1$ in.	$l = 14.15$ in.
$h = 5$ in.	$l = 19.15$ in.

Design of Primary Zone

The desired amount of air entering the primary zone was previously calculated to be .272 lb./sec. This required air flow was calculated by using the fact that the flow through the combustion chamber is parallel, i.e., the air once in the burner basket continues on through the basket and does not reenter any of the holes or slots on its way to the turbine. Therefore the friction pressure drop through any part of the burner must equal that through any other part. Using this fact along with a cut and try process for determining the size of holes required for the number desired, the design of the primary zone was completed as follows:

First, the weight flow through a set of four 13/32 in. primary holes was determined approximately by the formula:

$$w = \rho A_2 v C_0$$

Where w = air flow through the set of holes in lb./sec.

A_2 = area of the holes in ft.^{2}

ρ = density of air in lb./ft.^{3}

v = velocity of air through holes in ft./sec. and is taken as equal to that in the clearance area between the lines and the burner basket

C_o = orifice coefficient

C_o, the orifice coefficient, was obtained from a graph (Ref. 4) after computing Reynold's number and the diameter ratio as follows:

$$A_1 = \frac{b(H_o - H)}{2}$$

Where A_1 = clearance area at top or bottom between basket and burner shell at the location of the primary holes in ft.^{2}

b = basket width

H_o = outside height of clearance area in ft.

H = inside height of clearance area in ft.

$$A_1 = \frac{2}{12} \left[\frac{7.5 - 2(.222) - 4.8}{2 \times 12} \right]$$

$$= .01567 \text{ sq. ft.} = 2.256 \text{ sq. in.}$$

$$D_1 = \sqrt{\frac{A_1}{\pi/4}}$$

Where D_1 = diameter in ft. of a pipe with area equivalent to A_1

$$D_1 = \sqrt{\frac{.01567}{.785}}$$

$$= .1414 \text{ ft.} = 1.7 \text{ in.}$$

At this point it is assumed that .08 lb. air/sec. primary air is used for carbon prevention and cooling of forward end of combustion chamber.

$$v_1 = \frac{w_1}{\rho A_1}$$

Where v_1 = velocity in ft./sec. through clearance area

w_1 = air flow in clearance area in lb./sec. (two channels)

$$v_1 = \frac{(1.00 - .08)/2}{.0963 \times .01567}$$

$$= 305 \text{ ft./sec.}$$

From Ref. 5 pp. 53 and 54

$$\frac{\mu}{\mu_1} = \frac{T_1 + 216}{T + 216}\left(\frac{T}{(T_1)}\right)^{3/2}$$

Where μ = viscosity of the air in poises

$\mu_1 = .337 \times 10^{-6}$ lb.sec./ft.^{2} at $T_1 = 0^\circ F$

$T_1 = 0^\circ F$

T = temperature of air $200^\circ F = 660^\circ R$

$$\mu = .337 \times 10^{-6} \quad \frac{460 \quad 216}{660 \quad 216} \quad \frac{660}{460}^{3/2}$$

$$= .446 \times 10^{-6} \quad \frac{\text{lb. sec.}}{\text{ft.}^2} \text{ or } \frac{\text{slugs}}{\text{ft.sec.}}$$

Then:

$$NR = \frac{D_4 v_4 \rho_4}{\mu g}$$

Where NR = Reynold's number

g = gravitational constant = 32.2 ft./sec.

$$NR = \frac{.1414 \times 305 \times .0963}{4.46 \times 10^{-7} \times 32.3}$$

$$= .289 \times 10^{6}$$

$$A_2 = \frac{2\pi}{4}(13/32)^2$$

$$= 260 \text{ sq. in.} = .00181 \text{ sq. ft.}$$

$$\frac{D_2}{D_1} = \sqrt{\frac{A2}{A_1}} = \sqrt{\frac{.260}{2.256}} = .339$$

Then with these values of NR and D_2/D_1 and the chart from Eshbach (pages 6-35), C_o is found to be $\cong$ .60.

$$W = .0963 \times .00181 \times 305 \times .60$$

$$= .0317 \text{ lb./sec. for 1 channel}$$

$$= .0634 \text{ lb./sec. for both channels}$$

$$Q = \frac{W}{\rho}$$

Where Q = air flow through ring of holes in ft.^{3}/sec.

$$Q = \frac{.0634}{.0963} = 0.659 \text{ ft.}^3\text{/sec.}$$

The friction pressure drop was then calculated by the following formula from Ref. 6.

$$\Delta P = \frac{\rho}{2g}\left[\frac{Q}{A2Co}\sqrt{1-\left(\frac{A2}{A1}\right)^2}\right]^2$$

Where ΔP = friction pressure drop in lb./ft.^{2}

$$\Delta P = \frac{.0963}{66.4}\left[\frac{0.659}{.00360 \times .60}\sqrt{1-(.115)^2}\right]^2$$

$$= 136 \text{ lb./ft.}^2 = 0.95 \text{ lb./in.}^2$$

Since this was considered to be a reasonable value for friction pressure drop, it was selected as the value to be used in designing the combustion chamber.

Of the originally assumed .08 lbs.air/sec. for cooling and carbon prevention in the dome, the cooling part will be introduced by two 5/16 inch holes on either side of the fuel nozzle. The pressure drop equation is used to determine the air flow obtained through the holes.

$$Q = \frac{A_2 C_o}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}} \sqrt{2g \frac{\Delta P}{\rho}}$$

Where Q = air flow through the four 5/16 in. holes in ft.^{3}/sec.

A_2 = area of the four 5/16 in. holes in ft.^{2}

A_1 = area of the combustion chamber in ft.^{2}

$$A_2 = 4 \times \frac{\pi}{4} \left(\frac{(5/16)}{12}\right)^2$$

$$= .00213 \text{ sq. ft.} = .3068 \text{ sq. in.}$$

$$A_1 = 4.8 \times 2$$

$$= 9.6 \text{ sq. in.} = .0067 \text{ sq. ft.}$$

$$Q = \frac{.00213 \times .60}{\sqrt{1 - \left(\frac{.00213}{.0667}\right)^2}} \sqrt{\frac{64.4 \times 136}{.0963}}$$

$$= .3876 \text{ ft.}^3/\text{sec.} = .0373 \text{ lb./sec.}$$

The remaining air flow will enter through a slit between dome and the inner chamber wall. The flow thus is:

$Q = .08 - .0373$

$= .0427$ lb./sec. $= .444$ ft.^{3}/sec.

Since $\sqrt{1 - (A_2/A_1)^2} \cong 1$, the area required for the flow is obtained from the pressure drop equation:

$$A_2 = \frac{Q}{C_o \sqrt{2g\left(\frac{\Delta P}{\rho}\right)}}$$

Where A_2 = slot area in ft.^{2}

Q = air flow through the slot in ft.^{3}/sec.

$$A_2 = \frac{0.444}{.60\sqrt{64.4(\Delta P/\rho)}}$$

$= .00244$ sq. ft. $= .352$ sq. in.

The required thickness of each slot is found as follows:

$$\text{Slot thickness} = \frac{.352}{2 \times 2}$$

$$= .088 \text{ in.} \cong 3/32 \text{ in.}$$

Therefore the total air flow for primary section is .08 lb./sec. through and along outside of dome and 3 x .0632 or .1902 lbs./sec. through the three sets of 13/32 in. diameter holes. This totals .270 lb.air/sec. which is in close agreement with the required .272 lb.air/sec.

Design of Secondary Zone

The air flow through the secondary zone has to be 1 lb./sec. less the primary flow or .730 lb.air/sec. This air is

divided between the secondary holes entering the basket and the tail cone cooling passage.

Tail Section Cooling Passage

A 1/16 in. clearance between inner and outer combustion chamber at the tail end will be allowed for cooling the tail cone. To arrive at the velocity through the tail section in order to get the flow, the pressure drop equation of Ref. 6, page 84 is used.

$$\frac{\Delta P}{\rho} = \frac{f}{4}\,\frac{h}{R}\,\frac{v^2}{2g}$$

Where ΔP = friction pressure drop in lb./ft.^{2} = 136 lb./ft.^{2}

ρ = density of air in lb./ft.^{3} = .0963 lb./ft.^{3}

f = friction factor

h = length of tail cone in ft. $\cong$ 5/12 ft.

R = hydraulic radius in ft.

v = average velocity through slit in ft./sec.

Ref. 6 (page 74) gives the relation between f and Reynold's Number, NR. NR, in turn, is dependent upon v. Thus a cut and try calculation is necessary to arrive at values of f and v which will satisfy the equation.

From Ref. 6 (page 84):

$$NR = \frac{4v\rho R}{\mu g}$$

Where μ = viscosity in slugs/ft.sec.

$$R = \frac{A_{ave}}{WP}$$

Where A_{ave} = average cross-sectional area (1 channel) in sq. ft.

WP = wetted perimeter in ft. = $\frac{4}{12}$ ft.

$$R = \frac{.0625 \times 2/144}{4/12}$$

$$= .0026 \text{ ft.}$$

Assuming v = 240 ft./sec.

$$NR = \frac{4 \times 240 \times .0963 \times .0026}{.45 \times 10^{-6} \times 32.2}$$

$$= 16,600$$

and f = .0435

Solving for v to check assumption:

$$\frac{136}{.0963} = \frac{.0435}{4}\left(\frac{5/12}{.0026}\right)\frac{v^2}{64.4}$$

$$v = 230$$

Since this is a fairly close check, the velocity is approximately 225 ft./sec.

$$Q = Av$$

Where Q = flow through tail section passages.

$$Q = .000869 \times 225 \times 2$$

$$= .391 \text{ cu.ft./sec.} = .0376 \text{ lb./sec.}$$

Secondary Holes

Knowing the flow through the primary zone, and the tail

section passages, the weight flow through the secondary holes is the remainder, or:

$$Q = 1 - .270 - .0376$$

$$= .692 \text{ lb.air/sec. flow through secondary holes.}$$

In computing the air flow through the secondary holes, an additional flow coefficient, effectiveness coefficient, C_e, is used due to the high velocity in the combustion chamber producing an angularity of flow through the secondary holes. This angularity of flow was taken to be 45° as a result of the experiment conducted to simulate the flow in Ref. 2. C_e is defined as the sine of the angle of flow.

$$C_e = \sin 45^\circ$$

$$= .707$$

To find the flow through 1 set of four 5/8 inch diameter holes:

$$Q = N_h A_2 C_e C_o \sqrt{2g \frac{\Delta P}{\rho}}$$

Where Q = airflow through set of holes in ft.^{3}/sec.

N_h = number of holes in set = 4

A_2 = area of each hole = .3068 in.^{2} = .00213 ft.^{2}

C_e = effectiveness coefficient $\cong$ .707

C_o = orifice coefficient = .60

g = gravitational constant = 32.2 ft./sec.^{2}

ΔP = friction pressure drop = 137 lb./ft.^{3}

ρ = density of air = .0963 lb./ft.^{3}

$$Q = 4 \times .00213 \times .707 \times .60 \sqrt{64.4 \times 137/.0963}$$

$$= 1.093 \text{ ft.}^3/\text{sec.} = .1051 \text{ lb./sec.}$$

Similarly, Q for a set of four $\frac{1}{2}$ inch diameter holes is .0671 lb./sec. and for a set of two 7/16 inch diameter holes is .0262. Thus five sets of 5/8 inch diameter holes, one set of 1/2 inch diameter holes, and four sets of 7/16 inch diameter holes produces 0.697 lbs.air/sec., which is very close to the required .692 lb.air/sec.

Check for Air Flows

	.1902 lb./sec.	three sets of 13/32 inch holes
	.0373 lb./sec.	four 5/16 inch holes in dome
	.0427 lb./sec.	slit between dome and inner bracket
	.0376 lb./sec.	tail section cooling passage
	.0674 lb./sec.	one set of 1/2 inch holes
	.5255 lb./sec.	five sets of 5/8 inch holes
	.1048 lb./sec.	four sets of 7/16 inch holes
Total	1.0055 lb./sec.	total air flow

Location of Holes

The primary air should be introduced far enough downstream to insure the development of a strong combustion eddy. This is about three-fourths to one diameter from the fuel nozzle.

The secondary air should be first introduced at a low rate and then at an increasingly greater rate downstream. This is to prevent chilling of the flame front and the resulting stoppage of the combustion process.

A convenient method for locating the primary and secondary holes to satisfy these requirements was developed by J. B. Verdin (Ref. 2), and is shown in Figure 2 and tabulated in Table I. The total area of the openings into the basket is plotted vs. distance from the fuel nozzle. The curve shown is an arc of a circle and is defined as follows:

1. The center of the circle lies on the verticle line through the zero distance point.
2. One point on the arc is the area of the openings into the burner basket ahead of the fuel nozzle, i.e., the area of the four 5/16 inch holes. This area is plotted at the point of zero distance.
3. The other point of the arc is the total area of all the openings and slots in the burner basket. This area is plotted at the distance at which the

last row of secondary holes is desired.

After construction of this curve in Figure 2, the area of the sets of holes were fitted to it as closely as possible with proper distance left between holes for manufacturing reasons

APPENDIX B

Shutter Speed Calculations

Moment of Inertia of the .032 inch thick aluminum disk, half of which is one foot in radius and the other half eleven inches in radius:

$$I = \frac{mr^2}{2}$$

where m = mass of aluminum disk

r = radius of disk

$$\text{Area of disk} = \pi r^2 = \pi\left(\frac{12^2}{2} + \frac{11^2}{2}\right)$$

$$= 416 \text{ sq. in.}$$

With a 4 inch diameter shutter hole in the disk, the corrected area is 416 - 13 = 403 sq. in. The weight of .032 inch thich aluminum sheet is .451 lbs/sq ft, or .00313 lbs/sq.in. Weight of disk = .00313 x 403 = 1.24 lbs.

$$\text{Mass of disk} = \frac{w}{g \times 12} = \frac{1.24}{386}$$

$$= 0.00320 \text{ lbs sec}^2/\text{in.}$$

$$I_{disk} = \tfrac{1}{2} mr^2 = \frac{.00320}{2}\left(\frac{144}{2} + \frac{121}{2}\right)$$

$$= .212 \text{ lb.in.sec}^2$$

Pulley Moment of Inertia

Area of the 7 inch diameter pulley

$A = \pi r^2 = \pi(3.5)^2$

$= 38.3$ sq. in.

Weight of aluminum plate 0.23 in. thick is 3.23 lbs/sq ft =

.0224 lbs/sq in

Pulley weight = 38.3 x .0224

= .860 lbs

$I_{pulley} = \frac{1}{2}\frac{w}{g}r^2 = .0136$ lbs in sec^2

Total Moment of Inertia of Disk and Pulley

$I_{total} = .212 + .0136$

$= .226$ lb in sec^2

Two very fast acting springs were used for actuating the shutter which produced a total 60 lb pull when stretched 11 inches. Under this condition the energy stored by the spring is:

$E = 2 \times \frac{1}{2} \times 30 \times 11$

$= 330$ in lbs

Neglecting friction losses, this energy will become the kinetic energy of the rotating shutter.

$KE = \frac{1}{2}I_T\omega^2$

Where ω = angular velocity (radian/sec)

$$\omega = \frac{2\ KE}{I_{total}} = \frac{2 \times 330}{.226}$$

$$= 54.0 \text{ radians/sec.}$$

Mean velocity of shutter at time of exposure is

$$v = r\omega$$

Where r = mean shutter radius = 8 in.

$$v = 8 \times 54.0 = 432 \text{ in/sec}$$

Time of exposure produced by the 4 inch diameter hole is

$$\text{Exposure time} = \frac{4}{432} = .0092 \text{ sec.}$$

Making allowance for the friction between the metal shaft of the rotating disk and its retainer in the shutter mount results in a shutter exposure time of approximately 1/100 second.

APPENDIX C

Sample Calculation of Combustion Chamber Air Flow

Test Conditions

Barometer = 29.18 in.Hg

Temperature = 80°F

ΔP = 0.55 in. water, nozzle velocity head.

$$w = C_o \rho VA = C_o \rho A \sqrt{2g\,\frac{h\,\rho'}{\rho}}$$

Where w = air flow in lb/sec

C_o = nozzle coefficient = 0.98

ρ = density of air = P/RT = .0718 lb/cu ft.

ρ' = density of water = 62.3 lb/ft^3 at 80°F

A = nozzle area = .2675 sq. ft.

h = pressure head in feet of water at nozzle

= 0.55/12 ft of water

$$w = .98 \times .0718 \times .2675 \times \sqrt{\frac{2 \times 32.2 \times .55 \times 62.3}{.0718 \times 12}}$$

= .953 lb air/sec

APPENDIX D

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